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Façades	A	B	C	D
A	-	21	22	21
B	3	-	19	17
C	2	5	-	6
D	3	7	18	-

Table 1. The table reports the dominance matrix for the paired-comparison task.

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Can curvature drive preference for architectural façades and their perceived familiarity, complexity, stability or approachability? In this study we aimed to investigate if the well-known preference for curvature can be extended to the architectural domain. We generated four different versions of the same reference building, varying only the amount of curvature of the façade. Twenty-four participants 1) made a preference forced-choice task between pairs of stimuli; 2) ranked all stimuli from the most to the least preferred; 3) evaluated each stimulus on different psychological variables. Multidimensional scaling on forced choices showed that the curved façade was the most preferred. Multidimensional unfolding on the ranking task showed that the majority expressed higher preferences for the curved facades compared to sharp-angled and rectilinear ones. Ratings on different psychological variables gave supporting evidence for curvature significantly influencing liking and approaching judgments. We then processed the stimuli with a dynamical model of the visual cortex and a model that characterises discomfort in terms of adherence to the statistics of natural images. Results from these image analyses matched behavioural data. We discuss the implications of the findings on our understanding of human preferences, which are intrinsically dynamic and influenced by context and experience.

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Introduction

Architects frame space, design geometries and study buildings' proportions to convey ideas and emotionally engage the visitor. The 20th century unbuilt project of the Italian architects P. Lingeri and G. Terragni (1938), the Danteum, is a striking example of a building planned to have no other function except to tell the story of Dante's Divine Comedy (Figure 1). The idea that the structure and shape of the environment we live in can influence our social behaviour and our affective state can be traced up to Vitruvius (15 B.C.). Principles of *utilitas* (functionality), *firmitas* (stability) and *venustas* (aesthetics) influenced the most prominent architects and artists of Italian Renaissance: Alberti, Palladio, Brunelleschi, Borromini, Bramante and Leonardo da Vinci. Vitruvian terms like order, proportion and symmetry are still a reference point for experts nowadays. For example, in the Design Quality Indicator (DQI; Gann, Salyer & Whyte, 2003) authors started directly from the three old Vitruvian principles to develop the three modern concepts of: function, build-quality and impact.

Figure 1. From left to right: perspective of the Hell, the Purgatoire and the Heaven rooms of the Danteum's project by P. Lingeri, G. Terragni (1938, Archivio Pietro Lingeri, Milano). Retrieved from: http://www.fupress.net/index.php/oi/article/viewFile/19687/18808

In the contemporary era, we can outline two main trends characterising architecture design: 1) the 'modernist' approach, inspired by the creed 'form ever follows function' (Sullivan, 1896) that prioritises the function of a building over its aesthetics; and 2) the 'human-centred design' approach, characterised by the effort to capture and potentially predict the impact of architecture and urban design on human behaviour (Shaftoe 2008; Gutman 2009; Zhang & Dong, 2009). Since the 70's, approaches like organic architecture (Wright, 1958; Hildebrand, 1991, 1999), bio-architecture (Aguilar, 2003) and biomimicry (Gendall, 2009) started to flourish, combining the use of sustainable resources to basic configurations developed from existing natural shapes and promoting the buildings' integration in nature. Theoretical frameworks interpreting environmental preference for landscapes and built environments (Appleton, 1992, 1996; Hildebrand,

1991) stressed the potential positive impact that particular combinations of shapes might have on users' emotional experience of space (Lidwell et al. 2010; Lippmann 2010). The main aim of this study is to investigate the role of geometry in the architecture domain, with a particular focus on the influence of curvature in driving human's preferences. We will outline key findings from literature to create a theoretical context for relevant issues that can be extended to the field of architectural design and urban planning.

The curvature effect

In psychology, the 'curvature effect' is a well-known and consistent phenomenon (Bar & Neta, 2006, 2007; Silvia & Barona, 2009; Leder et al., 2011; Palumbo et al., 2015; Bertamini et al., 2016; Vartanian et al., 2013, 2015), yet still not well understood.

In their classical studies, Bar and Neta (2006, 2007) showed that objects and abstract shapes were preferred in their curved version compared to the sharp-angled one and a significantly greater activation of the amygdala for the sharp-angled objects compared to their curved version (Bar & Neta, 2007). Due to the neutral valence of their stimuli, the authors interpreted the amygdala activation as threat-related, suggesting that sharp-angled contours convey a sense of threat *per se* and that preference for curvature is a by-product of disliking sharpness (Bar & Neta, 2007). However, this interpretation has been challenged by other studies using different methodologies, addressing implicit associations and approach/avoidance responses to curvature (Palumbo et al., 2015). In their second experiment, Palumbo et al. (2015) showed that participants were faster and more accurate when the task was to move a human-stick figure towards curved shapes, but there was no difference in the RTs when the task was to approach or avoid sharp-angled shapes. The authors conclude that curvature might be preferred for its intrinsic aesthetically pleasing properties, but also be influenced by the emotional valence of positive, safe and female concepts shown to be implicitly associated with curved shapes –as they showed in the first experiment (Palumbo et al., 2015).

In the extensive review on the theme, Gómez-Puerto, Munar and Nadal (2016) identify two main approaches that shaped the research of the past two centuries:

1) the first one, focusing on the physical properties and the perceptual mechanisms involved in preference for curvature, explaining the phenomenon from a sensorimotor-based or a valuation-based perspective;

2) and the other oriented towards the investigation of the origins and the possible function of this preference, divided between culturally influenced or biologically determined explanations.

Moreover, research has shown that preference for curvature can be mediated by the emotional valence of the stimuli (Leder at al., 2011), participants' expertise (Silvia and Barona, 2009) and cultural context or aesthetic *Zeitgeist* (Leder & Carbon, 2005; Carbon, 2010). Hess and colleagues (2013) showed that abstract sharp-angled shapes could also modulate perceived aggressiveness of a face as well as our social behaviour. While assembling a puzzle, participants tended to judge the resulting faces as more aggressive if the puzzle was made by sharp-angled compared to curved elements. In the second experiment they showed that participants were more likely to make an aggressive decision in a role-playing trust game if sharp-angled shapes compared to curve shapes decorate the experimental setting. Gómez-Puerto et al. (2016) conclude that there is enough evidence in the field to support preference for curvature as being both the result of a learnt process as well as an evolved one.

Preference for curvature in architecture: what do we know so far?

Experimental research reported contrasting results also when using architecture images. In the fMRI studies conducted by Vartanian and colleagues (2013, 2015), participants looked at images of architectural interiors and then judged them on different psychological variables. The study reported that curved interiors were more likely to be perceived as beautiful compared to rectilinear ones, but the geometry was not a critical factor for approachability decisions. Neuroanatomical results showed that looking at curved spaces activated the anterior cingulate cortex (ACC) exclusively, a brain region which is known to be linked to reward and being a core circuit for aesthetic processing. In contrast, rectilinear interiors did not show a significant amygdala activation, as previously found by Bar and Neta (2007). The authors put forward the hypothesis that, in architecture, sharp-angled contours may have lost their threatening valence, as an effect of mere exposure (Marks & Dar, 2000; Zajonc, 2001).

If we exclude the studies by Vartanian et al. (2013, 2015), there is a very limited number of researches that explicitly controlled for the amount of curvature/sharpness of the stimuli involved, especially when representing an artificial environment. Leder and Carbon (2005) tried to isolate the cultural influence on preference for curvature using a series of sketches inspired by actual car design, manipulating their complexity, innovativeness and amount of curvature. Their findings confirmed the role of curvature in significantly influencing attractiveness ratings, with a relatively small impact of participants' design knowledge. In another study on car design, Carbon (2010) provided empirical evidence for the dynamic nature of this preference by explicitly instructing participants about the cultural context and historical design tends (*Zeitgeist* effect). After adaptation to futuristic car design, perceived innovativeness became a better predictor for participants' liking judgments compared to curvature (Carbon, 2010).

Research in environmental psychology has not provided conclusive results about the importance of geometry in architecture either. In the meta-analysis conducted by Dosen & Ostwald (2016) only five out of the thirty-four analysed studies directly manipulated the geometry of the space, using environments' computational simulations.

In a recent study, Shemesh et al. (2016) validated a new methodology combining psychological and neurophysiological measures (EEG) with Virtual Reality (VR) in order to capture in a more controlled way the dimension of spatial interaction with the environment. This is one of the very first studies, to the best of our knowledge, directly controlling for the global geometry and the symmetry of the architectural space presented in the experiment. They created four types of virtual environments, controlling for curvature and symmetry. They analysed the EEG data using a two-steps manifold learning technique: the first step identified the EEG channels relevant for geometry processing (Lederman & Talmon, 2015); while the second step analysed the activity of those selected channels (Talmon et al. 2015). The study showed encouraging results for differentiating brain activity in response to the different geometries. The authors found that curvature, but not symmetry, had a significant impact on VR users' preference overall, with a significant effect of participants' design expertise: non-experts rated curved spaces as more interesting compared to experts.

It is important to point out how previous research showed contrasting results on the role of expertise in modulating preference for curvature: Silvia and Barona (2009) reported a significant interaction between expertise and curvature: in the first experiment with simple polygons the effect was stronger for novices; while in the second experiment, that used more complex shapes, experts showed a greater preference for curvature. Mass et. al. (2000) reported that architectural façades judged as beautiful were also perceived as intimidating by lay people (Maass et al., 2000), and Cotter et al.

(2017) showed how preference for curvature is linked with art expertise and openness to experience personality trait.

What can we learn from image analysis?

One of the key arguments used by the biologically determined explanations is that curved lines are more occurring in nature. From this assumption derives that sharp-angled shapes are perceived as threatening because they are difficult to find in organic environments (Gómez-Puerto et al., 2016). We know that natural images, namely images of natural scenes, have special statistical properties, and that these properties can be processed more efficiently by the human visual system (Field, 1987; Geisler 2007). Based on these characteristics, Penacchio and Wilkins (2015) developed an algorithm that robustly predicts visual discomfort in terms of adherence to the statistics of natural images: the more an image deviates from the statistics of natural images, the more likely it is to be judged as uncomfortable to look at. Repetitive patterns such as high contrast gratings, whose image statistics strongly deviate from the statistics of natural images, are particularly uncomfortable to look at, especially if the spatial frequencies involved correspond to those best perceived by the human visual system (Fernandez & Wilkins, 2008; Juricevic, Land, Wilkins, & Webster, 2010; Penacchio & Wilkins, 2015). Computational models suggest that detrimental patterns and images with unnatural statistics are processed less efficiently by the brain as they cause a denser response (more neurons firing at the same time) in the visual system (Hibbard & O'Hare, 2014; Penacchio et al., 2016), which can be at the origin of visual discomfort. Le et al. (2016) reported that images of urban scenes with statistical properties that deviate from the typical statistical properties of natural scenes were associated with a higher haemodynamic response in the visual cortex. They also found that judgments of visual discomfort from real scenes were matched to judgments from images of these scenes, suggesting that this measure could be integrated into the design practice of urban scenes to avoid constructions with detrimental consequences for brain metabolism, and also for health and wellbeing.

Literature offers useful insights about curved shapes driving our preferences for built environments and objects surrounding us, but also highlights the need to investigate the role played by individual differences (e.g.: personality traits) and explicit knowledge (e.g.: expertise) in modulating this effect. We can highlight four limits of the body of research reported so far, relevant when trying to generalise these findings to the architecture domain:

(1) most of research used very simple or abstract stimuli;
(2) often the stimuli are presented on computer screens, making difficult to generalise results to real spatial interaction with architectural geometries;
(3) the studies measured primarily liking judgments;
(4) there are technical issues in the control for global and local amount of curvature introduced in more complex stimuli, especially when representing architectural spaces, as usually researchers in psychology do not have expertise on 3D modelling.

We suggest that those limits can be addressed directly engaging in a dialog with professional architects, defining research questions relevant for both psychological science and architecture design. Collaborating with experts in architecture allows to create stimuli more ecologically valid and to have a better control the geometry of the built space, rather than trying to match or modify pictures of already existing buildings. We believe that a multidisciplinary approach is needed when studying complex phenomena like the curvature effect, to explain its multiple aspects and implications.

Starting from those preliminary considerations, in the present study we wanted to test the robustness of the 'curvature effect' not only exploring judgements of façades as isolated stimuli, but also directly comparing different versions of the same building (controlling for local and global features). We collected preferences with three different methods: a forced-choice task, ratings on a series of psychological variables for each façade and a classification task.

Material and Methods

Participants

Twenty-four female participants gave informed consent before taking part in the experiment. All were volunteers and were recruited from the student population of the School of Education of University of Roma Tre. All had normal or corrected-to-normal vision. The experiment was conducted in accordance with the Declaration of Helsinki (2008). Preference for curvature has been shown not to be subjected by gender differences (Frantz & Miranda, 1975; Jadva et al., 2010; Palumbo et al., 2015), so we have evidence to support the fact that having a sample made of all women will not bias our data.

Stimuli

We adopted a similar approach to Leder and Carbon (2005) and controlled for both global and local features of our stimuli, gradually increasing the amount of curvature introduced in the architectural façade. Knowing that positive emotional valence modulates the preference for curved objects (Leder et al., 2011), we wanted to control the affective valence associated with the architectural style of our stimuli. Previous studies (Mastandrea, Bartoli & Carrus, 2010; Chirumbolo, Brizi et al., 2014;

Mastandrea, & Maricchiolo, 2014) showed that lay people find easier to implicitly associate figurative art, classical architecture and design objects to positive concepts compared to abstract art and modern architecture. We choose as reference building the Oratorio dei Filippini (Oratory of Saint Phillip Neri, 1637-1650) by Francesco Borromini (Figure 2), one of the most representative architects of the Baroque style, close to the classical buildings used in previous research investigating affective valence of architecture design (Mastandrea, Bartoli & Carrus, 2010).

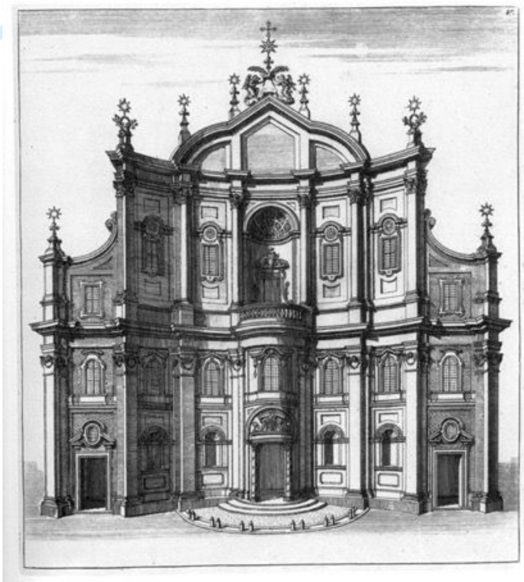

Figure 2. Engraving of the façade of Francesco Borromini's Oratorio dei Filippini by Domenico Barrière (1658). Retrieved from: https://commons.wikimedia.org/wiki/File:Borromini_Drawing_01.jpg

Following the terminology guidelines proposed by Gómez-Puerto, Munar and Nadal (2016), we will refer to the characteristics of our stimuli as curved and sharp-angled. We availed ourselves of the expertise of the architect S. Lamaddalena to create the stimuli for this study, using the professional software application AutoCAD (version 2.0, 2015). Together with her, we defined the architectural features to manipulate in the stimuli as follows:

1. global: the overall shape and outline of the façade;
2. local: windows, columns and other decorative elements on the façade.

The final stimuli developed from these concepts consisted of four simplified 2D models of the reference building, whose global and local architecture features varied reflecting the following characteristics:

- A, curved;
- B, mixed;
- C, rectilinear;
- D, sharp-angled.

All religious references in the façades were removed, to avoid interactions with participants' religious affiliation.

One of the main predictions deriving from Berlyne's classical work on aesthetic experience, is that people tend to prefer medium levels of complexity (Berlyne, 1970), and we know from previous findings that sharp-angled shapes are judges as more complex compared to curved ones (Bertamini et al., 2016). Taking in account those evidences, we hypothesised the mixed façade (B) to be judged as having a medium level of complexity and, consequently, to be preferred over the other versions –being also the closest to the original design of the reference building. Bertamini et al. (2016) found that preference for patterns od simple lines was higher for the curved version, followed by rectilinear and sharp-angled. The rectilinear façade (C) was created as a control condition, in the attempt to replicate the findings by Bertamini et al. (2016) in the architecture domain.

Figure 3. The four architectural façades we used in our study. In alphabetical order: curved (A), mixed (B), rectilinear (C) and sharp-angled (D) version.

Procedure

In order to simulate a more ecological situation, we presented the images of architectural façades on a big projection screen rather than on a small computer monitor. The experimental apparatus consisted of a 150 cm x170 cm projection screen in a darkened classroom. All participants were seated at approximately 250 cm from the screen. Stimuli were presented using an Epson Eh - tw5650 projector (2.500 lumen, full HD, contrast at 60.000:1) and occupied 176° of visual angle. During the experiment participants were not allowed to talk with each other and two researchers supervised the room to guarantee the tasks to be performed accurately and independently.

Being aware of the conflicting results reported on expertise in preference for curvature (Silvia & Barona, 2009), we decided to control for expertise even if people in our sample did not have any formal training in art. According to the model of aesthetic appreciation outlined by Leder et al. (2004), we know that art interest plays an important role in aesthetic appreciation. Before starting the experimental session, we asked participants to self-assess their level of art interest on a five-point Likert scale (where 5 = "Very much" and 1 = "Not at all")[1], as a way of quantifying expertise among non-experts.

The current study consisted of three experimental blocks. Each block was associated with a customised printed grid, as described below in more detail. The main aim of our procedure was to test if preference for curvature is task-independent.

The first block consisted of a two-alternatives forced choice task. We presented for 3 seconds each of all the possible six combinations of the four façades, without repetitions: AB; CD; BC; AD; CA; DB. Each façade was presented three times in total and the order was counterbalanced, to make sure that each version appeared at least once on the left-hand side of the projection screen. After the stimuli disappeared the screen was blanked, and participants were asked to record their preferred façade on a printed grid. The grid consisted of six rows, one for each repetition, and were divided into two cells. If participants preferred façade presented on the left-hand side of the screen, they were asked to tick the left cell on the printed grid; if they preferred the façade on the right-hand side, to tick the right cell.

During the second block, participants performed a multiple rating task. They were asked to rate each façade using a five-point Likert scale (where 1 = "not at all", 2

= "slightly", 3= "somewhat", 4 = "moderately" and 5= "very much"[1]). The façades were presented on screen one at the time and were identified by a letter previously assigned by the researchers, as illustrated in Figure 3. Participants were asked to collect ratings on a customised printed greed for five psychological dimensions: liking, familiarity, complexity, stability and approach[2]. Participants performed the liking ratings first, to assure that liking would not be affected by the other measures.

Finally, in the third block participants had to perform a rating task. The four façades were presented all at the same time on screen, arranged as shown in Figure 3. Each stimulus was identified by the same letter as the one used in the second. The customised grid consisted of four squares, arranged in a row. Participants had to fill the squares with the letters identifying each stimulus, arranging the façades from the most (=1) to the least (=4) preferred.

Data analysis and Results

Due to the nature of our procedure, we report the results from the three different experimental blocks separately.

First block: two-alternatives forced choice

The results of the two-alternatives forced choice experiment are summarized in the dominance matrix reported in Table 1: each positive entry represents the number of

[1] Original items in Italian were: 1 = "per niente", 2 = "poco", 3= "abbastanza", 4 = "molto" and 5= "moltissimo"

[2] Original items in Italian were: "Quanto ti piace questo edificio?" "Quanto ti è familiare questo edificio?"; "Quanto è complesso questo edificio?"; "Quanto è stabile questo edificio?"; "Quanto questo edificio ti invita ad entrare?".

times the row façade was preferred to the column façade, and main diagonal elements are conventionally set to zero. All the corresponding off-diagonal elements satisfy a constant sum property (e.g.: all pairs of corresponding entries (*i*,*j*) and (*j*,*i*) sum up to 24), resulting in the sum of row and column totals for each façade being also constant. Thanks to this way of representing data, we can easily obtain the façades preference order by the row totals of the dominance matrix, that is –from the most to the less preferred:

- A (curved);
- B (mixed);
- D (sharp-angled);
- C (rectilinear).

A second consequence of the previous properties is that symmetry is not interesting in this matrix, but it is worthwhile to focalize on the skew-symmetric information. The skew-symmetry of each pair of façades is the difference of the corresponding frequency in the matrix by the value 12, which in our experiment corresponds to the situation of equilibrium (12 subjects prefer one façade and other 12 subjects prefer the other one).

Façades	**A**	**B**	**C**	**D**
A	-	21	22	21
B	3	-	19	17
C	2	5	-	6
D	3	7	18	-

Table 1. The table reports the dominance matrix for the paired-comparison task.

The skew-symmetric component of a dominance matrix can be depicted by a method of asymmetric multidimensional scaling proposed by Bove (2011, 2012), which adapted the idea originally proposed by Okada & Imaizumi (1987) for asymmetric proximities to skew-symmetric data. This method represents the architectural façades as points in a two-dimensions diagram. Both the façade preference orders and the imbalances are represented: the former as circles with different radii (larger circles correspond to higher ranks of preference), the latter as the distances between points (larger distances correspond to lower equilibrium). Results are shown in Figure 4.

The size of the circles shows the overall preference order: A, B, D, C. Façade A is the most preferred and is liked equally more than B, C and D. Façades B and D have the smallest imbalance between each other, so they are represented as closer on the plane. Façade C is the last on the preference order with no ray. It is dominated by all the other façades, but much more by A and B that are positioned further away from it.

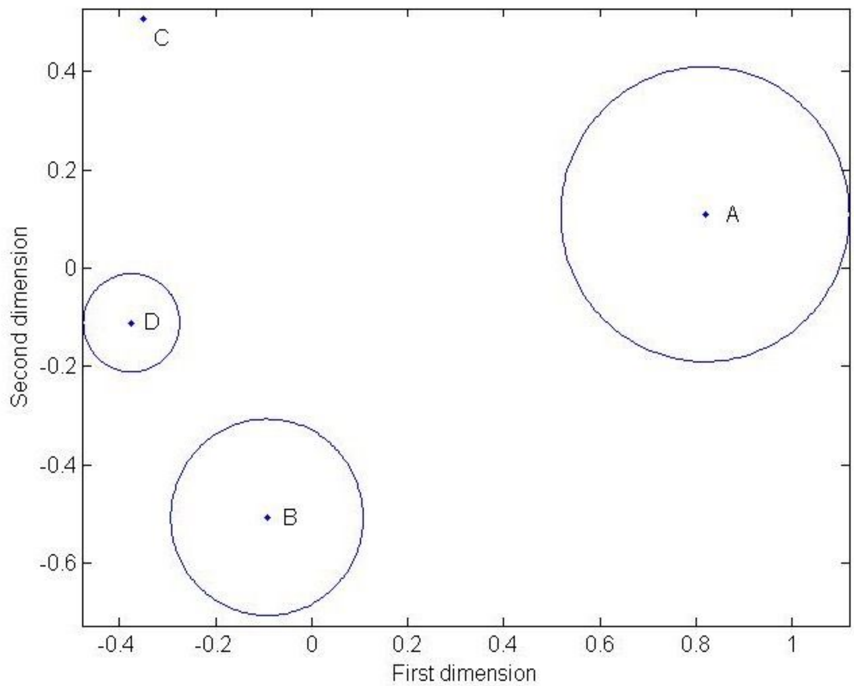

Figure 4. Asymmetric multidimensional scaling representation for data in Table 1.

354 ***Second block: multiple rating tasks***

355 Five one-way repeated measure ANOVAs were conducted on rating values for each of
356 the five psychological variables we measured (liking, approach, complexity, stability
357 and familiarity), with façade version (A, B, C and D) as independent variable. There
358 was no significant difference for familiarity ratings ($F(3,69)= 2.375$, $p = .078$ NS),
359 suggesting that the simple design of our stimuli did not interfere with the perceived
360 familiarity of the architectural style of the façades. All the other psychological
361 dimensions had a statistically significant main effect: liking ($F(3,69)= 13.077$, $p = .000$),
362 approach ($F(3,69)= 12.375$, $p = .000$), complexity ($F(3,69)= 13.162$, $p = .000$) and
363 stability ($F(3,69)= 3.060$, $p = .034$).

364 Post hoc tests using the Bonferroni correction revealed that liking (1.8 ± 0.35),
365 approach (2.08 ± 0.37) and complexity (2.3 ± 0.22) mean ratings for the rectilinear
366 façade –C— were statistically significantly lower than mean ratings for the other
367 façades ($p < .05$). It is relevant to report the façades' rating order for each of the
368 measured variables, from the most to the least rated:

369 • A, D, B, C for liking and approach;
370 • D, A, B, C for complexity;
371 • C, B, A, D for stability.

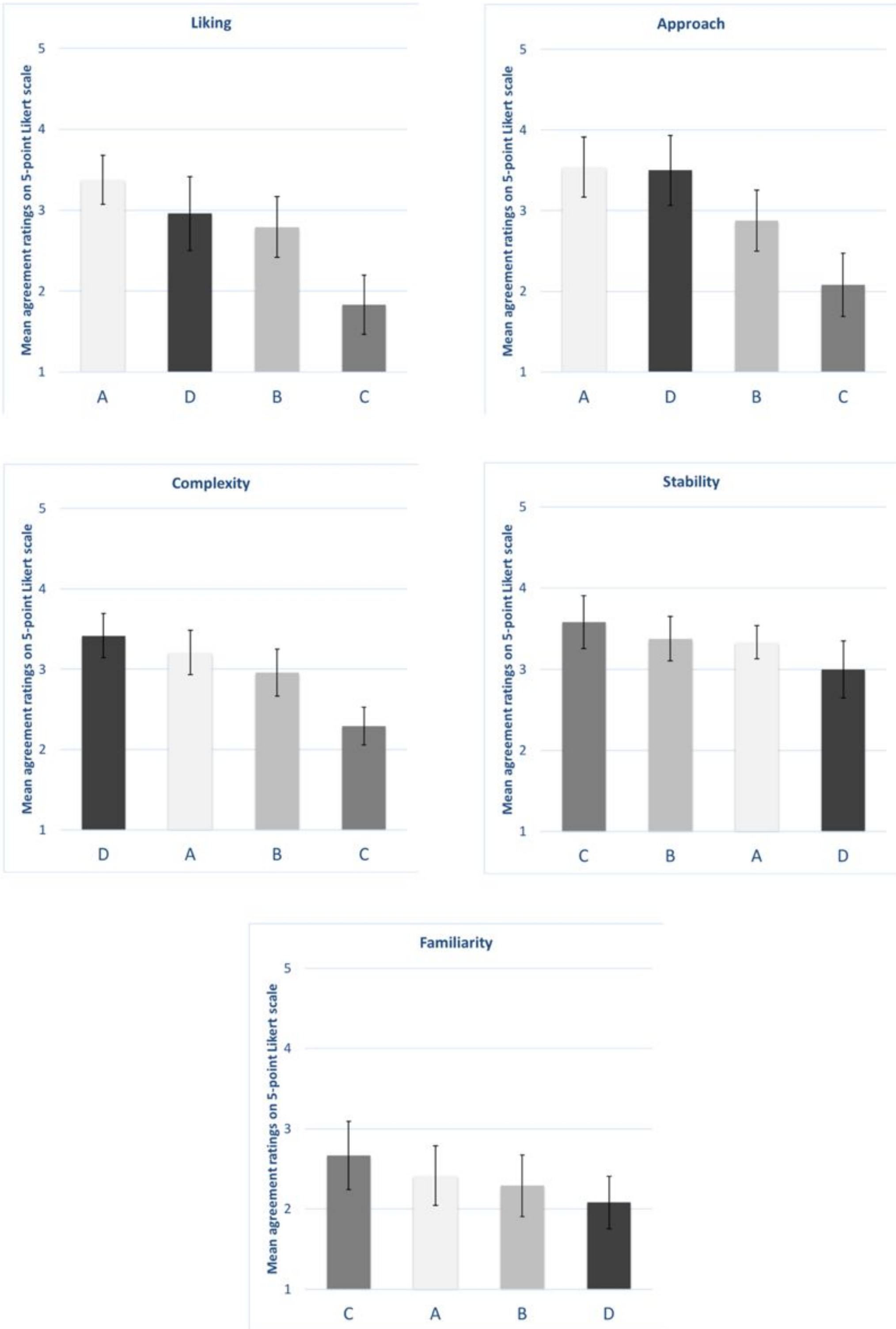

Figure 5. The graphs show the average score obtained by each building across the five variables. From top to bottom, left to right: liking, approach, complexity, stability and familiarity –bottom middle—. Error bars represent confidence intervals.

376 ***Third block: ranking task***

377 The analysis of the frequencies we collected for the ranking task confirmed the
378 preference order showed in the two-alternatives forced choice task as the ranking order
379 was A, B, D and C. Table 2 reports the number of times each façade (row) was chosen
380 in an order position (column) by participants.

	First	Second	Third	Fourth
A	15	5	3	1
B	5	13	6	0
C	1	0	2	21
D	3	6	13	2

381 Table 2. The table reports the frequencies of order choices in the ranking task.
382

383 Besides, we analysed the (24×4) preference data matrix with multidimensional
384 unfolding technique (Borg & Groenen, 2005) to explore possible relationships between
385 subjects and façades. The results from this analysis are shown in Figure 6, where
386 numbers represent the subjects and letters represent the façades.

387 According to the properties of the unfolding representation, the subjects tend to
388 be closer to the façades for which they expressed a higher rank in the task. Overall,
389 façade A – curved – and to a less extent façade B – mixed – are the two main buildings
390 around which the gather majority of the subjects is placed, including the one with the
391 highest self-reported artistic interest. Subjects 4, 9 and 15 preferred façade D, but their
392 artistic interest rank was of 2, corresponding to a medium-low level. Only one subject
393 (subject 14) preferred façade C, but had also the lowest level of artistic interest,
394 corresponding to no artistic interest at all.

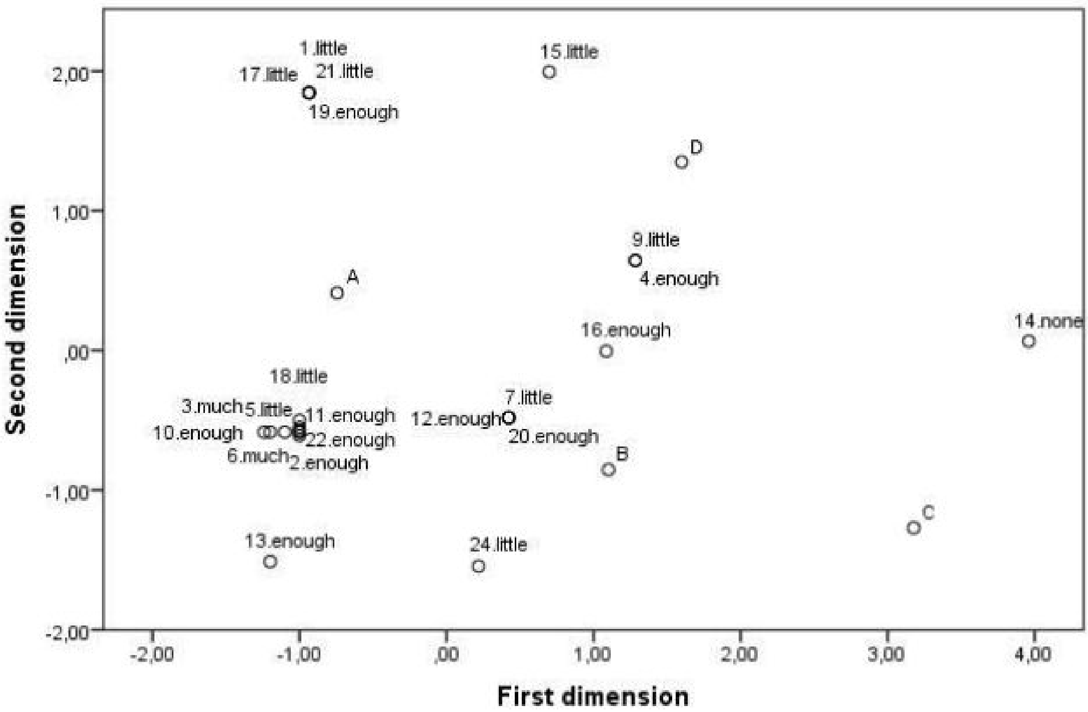

Figure 6. Multidimensional unfolding representation for rank order scores (Subject artistic interest level labels: none, little, enough, much).

Results from Image analysis

We used a model developed in Penacchio and Wilkins (2015) to analyse the stimuli. According to Fourier analysis, images can be decomposed into a sum of waves with different orientations, amplitudes and wavelengths –or spatial frequency. The amplitude of these waves as a function of spatial frequency is called the amplitude spectrum of an image. Natural images consistently have a very specific relationship between amplitude and spatial frequency: amplitude is proportional to the inverse of spatial frequency, a property often referred to as 1/f, where f stands for spatial frequency. This means that low frequencies have much more energy (or contrast) than high frequencies in natural images and that the fall-off statistically obeys the 1/f rule. The model we used essentially computes the extent to which an image amplitude spectrum departs from 1/f.

The model can also take into account anisotropy, the excess of energy that horizontal and vertical frequencies have in natural scenes and to which the visual system has adapted across evolution. Finally, when comparing the amplitude spectrum of an image to the typical amplitude spectrum of natural images, the model can give more weight to the spatial frequencies the human visual system is most sensitive to, namely frequencies around three cycles per degree (Campbell, 1968). Given an image, the model therefore provides a single number, called residual, that measures the extent to which the image deviates from the natural spectrum of natural images for a visual system differentially sensitive to some spatial frequencies. The lower the residual, the more similar to natural images the stimulus is. The model based on fundamental principles in efficient coding is a good predictor of visual discomfort (Penacchio & Wilkins, 2015).

The four different versions of the model (depending on whether anisotropy and the human sensitivity to different spatial frequencies are taken in to account) gave the same order of departure from natural images (i.e., the same order for the residuals): A (4.4), B (6), D (7.4), C (9). (The numbers reported here correspond to the residuals for the most general version of the model, see Penacchio and Wilkins, 2015.) The same order was also predicted by a mathematical model of the cortex. We processed the images with a mechanistic neurodynamical model of the visual cortex that includes the fundamental machinery underlying contextual modulation, namely excitatory and inhibitory neurons sensitive to different orientations as found in the primary visual cortex and lateral connections between them (Zhaoping Li 2002, Penacchio et al. 2013). The activity of this mechanistic model, which has been shown to encode comfortable images with a sparse activity (requiring only few neurons to fire strongly at the same time, as the visual cortex does in the presence of natural images) and uncomfortable images with a dense activity (Penacchio et al. 2016), ranked A, B, D and C, in conformity with the model based on Fourier analysis, and in line with a general theory of aesthetics based on the sensory coding of natural stimuli (Redies, 2007) and in line with the behavioural data.

Discussion

Our findings confirmed that curvature influenced preferences also for the stimuli representing architectural façades created for this study. Multidimensional scaling and unfolding provided graphical representations to easily detect preference order, size of asymmetry and relationships between subjects and stimuli (Maydeu-Olivares & Bockenholt, 2009; Piccolo, 2006). When participants directly compared different versions of the same building, the curved façade was the most preferred, followed by the mixed, sharp-angled and rectilinear, both in the two-alternatives forced choice (2AFC) and the ranking task. In both cases, the rectilinear stimulus was the least preferred and not the sharp-angled stimulus, as found in the previous study by Bertamini et al. (2016), that used patterns of simple lines. It is important to report that previous findings showed that different exposure time can modulate the curvature effect (Bar and Neta, 2006, 2007; Bertamini & Palumbo, 2016, Munar et al., 2015). The focus of the present study was to replicate those previous findings in the architecture domain. The aim for future research is to include different exposure time, to investigate the critical time span in which curvature has a significant effect in driving aesthetic preference, in modulating affective or emotional state and in influencing social behaviour.

The four architectural façades generated for this study were processed with the model described above (Penacchio and Wilkins, 2015) and with a dynamical model of the visual cortex (Penacchio, Otazu & Dempere-Marco, 2013, Penacchio et al. 2016). The order of stimuli preference was related in both models and matched to the behavioural data collected in this study and previous findings (Redies, 2007; Penacchio and Wilkins, 2015).

The hypothesis that preference for curvature derives from the optimal stimulation of the visual system might by itself explain this effect (Gómez-Puerto et al. 2016). We suggest creating a link between the statistical properties of natural scenes and that preference for curvature might have evolved from human interaction with natural environments. In support of this hypothesis, we report the interesting experimental investigation on the *Snake Detection Hypothesis* conducted by LoBue (2014). The author suggested that faster snake detection might not necessarily be due to perceiving threat but, more easily, to the basic perceptual mechanisms involved in detecting the curvilinear shape of those animals. Results from this study showed that participants were faster in detecting simple curvilinear shapes – so called snake-like stimuli— compared to their rectilinear counterpart, even in the absence of any threat-related information (LoBue, 2014). Our results seem to suggest that the image analysis approach used in the current study could be a valid way of quantifying curvature, which seems to be connected with predicted levels of image discomfort. We hope to better validate this methodology in future research, processing a richer set of stimuli and architectural styles, to investigate this link and its interaction with culture and expertise.

Results from individual ratings on liking, approachability, complexity, stability and familiarity showed a slightly different pattern and generated interesting insight. Both for liking and approachability the curved façade reported the highest ratings, followed by the sharp-angled version, which gained the second position over the mixed façade compared to the ranking and forced-choice tasks. The sharp-angled façade was judged as being the most complex, while the rectilinear the most stable. Previous findings reported that curvature did not affect approach-avoidance decisions for architectural interiors (Vartanian et al., 2013, 2015), however this was not the case for our study. We advance three possible explanations for these findings:

1) people might judge exterior prospects in a different way compared to interior living spaces and a better understanding of the psychological variables involved in approach-avoidance decisions is needed, in order to revise classical explanations –like perspective-refuge theory—and to stimulate interdisciplinary research;

2) the curved and the sharp-angled façades – those two showing the deepest gap between the central part and the extremes lateral corners of the façade— might have been perceived as physically projecting more towards the viewer compared to the other two versions, increasing the perceived approachability of the building for curved and sharp-angled version (see Fig. 2);

3) the rating order might have been influenced by the affective valence of the global and local features manipulated in our stimuli, in agreement with previous findings on aesthetics and on the meaning of rectangular shapes (McManus & Wu, 2013; Palumbo et al., 2015).

Results from this study present two main implications on future research:

(1) they provide empirical support for the hypothesis that preference for curvature might be stronger if compared to rectilinear rather than to sharp-angled features or stimuli presenting different amount of curvature;

(2) they shed light on the nature of human preferences, intrinsically dynamic and influenced by context and experience.

We should be cautious to generalise our results as they are on a very small sample of architectural stimuli, making hard to draw any more general conclusions. Following an emerging approach in current research of controlling the aesthetic qualities of stimuli (Leder & Carbon, 2005; Shemesh et al., 2016), future studies will aim to produce a more varied sample of architectural styles in order to investigate perceived approachability of interiors compared exteriors architectures, the role of buildings' function and cross-cultural differences, including measures like perceived innovativeness, interest (Carbon and Leder, 2005) or embodiment.

It is not hard to imagine that negative aesthetic reactions might be voluntarily induced by architects when designing buildings, using particular shapes and geometry. The 'Jewish Museum Berlin' (1989-2001) designed by Daniel Libeskind is an example of an architecture design that aims to induce a sense of fear, discomfort and dramatic absence in the visitor rather than liking or positive feelings. Knowing the critical role played by expertise in influencing curvature preference we suggest that architectural design practice might benefit from collaborating with scientific research, to better predict human perceptual as well as emotional reactions to the shape and geometry of buildings, aiming to plan better cities.

Disclosure statement

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References

Aguilar, Javier Senosiain. *Bio-architecture*. Routledge, 2003.

Alberti, Leon Battista. 1972. *Leon Battista Alberti: On painting (De Pictura).* Translated and edited by Grayson, Cecil. London: Phaidon. (Original work published 1436).

Appleton, Jay. 1992. “Prospects and refuges re-visited.” In *Environmental aesthetics: Theory, research, and application*, edited by Nasar, Jack L., 27–44, Cambridge University Press.

Appleton, Jay. *The experience of landscape*. Chichester: Wiley, 1996.

Bar, Moshe, Maital Neta, and Heather Linz. "Very first impressions." *Emotion* 6, no. 2 (2006): 269.

Bar, Moshe, and Maital Neta. "Visual elements of subjective preference modulate amygdala activation." *Neuropsychologia*45, no. 10 (2007): 2191-2200.

Berlyne, Daniel E. "Novelty, complexity, and hedonic value." *Perception & Psychophysics* 8, no. 5 (1970): 279-286.

Bertamini, Marco, Letizia Palumbo, Tamara Nicoleta Gheorghes, and Mai Galatsidas. "Do observers like curvature or do they dislike angularity?." *British Journal of Psychology*107, no. 1 (2016): 154-178.

Borg, Ingwer, and Patrick JF Groenen. *Modern multidimensional scaling: Theory and applications*. Springer Science & Business Media, 2005.

Bove, Giuseppe. "Analysis of skew-symmetry in proximity data." In *New Perspectives in Statistical Modeling and Data Analysis*, pp. 203-210. Springer, Berlin, Heidelberg, 2011.

Bove, Giuseppe. " Exploratory approaches to seriation by asymmetric multidimensional scaling." *Behaviormetrika* 39, no. 1 (2012): 63-73.

Campbell, Fergus W., and J. G. Robson. "Application of Fourier analysis to the visibility of gratings." *The Journal of physiology* 197, no. 3 (1968): 551-566.

Carbon, C. Christian, and Leder, Helmut "The repeated evaluation technique (RET). A method to capture dynamic effects of innovativeness and attractiveness." *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*, (2005): *19*(5), 587-601.

Carbon, Claus-Christian. "The cycle of preference: Long-term dynamics of aesthetic appreciation." *Acta psychologica* 134, no. 2 (2010): 233-244.

Chirumbolo, Antonio, Ambra Brizi, Stefano Mastandrea, and Lucia Mannetti. "'Beauty Is No Quality in Things Themselves': Epistemic Motivation Affects Implicit Preferences for Art." *PloS one* 9, no. 10 (2014): e110323.

Dosen, Annemarie S., and Michael J. Ostwald. "Evidence for prospect-refuge theory: a meta-analysis of the findings of environmental preference research." *City, Territory and Architecture* 3, no. 1 (2016): 4.

Fantz, Robert L., and Simon B. Miranda. "Newborn infant attention to form of contour." *Child Development* (1975): 224-228.

Fernandez, Dominic, and Arnold J. Wilkins. "Uncomfortable images in art and nature." *Perception* 37, no. 7 (2008): 1098-1113.

Field, David J. "Relations between the statistics of natural images and the response properties of cortical cells." *Josa a*4, no. 12 (1987): 2379-2394.

Gann, David, Ammon Salter, and Jennifer Whyte. "Design quality indicator as a tool for thinking." *Building Research & Information* 31, no. 5 (2003): 318-333.

Geisler, Wilson S. "Visual perception and the statistical properties of natural scenes." *Annu. Rev. Psychol.* 59 (2008): 167-192.

Gendall, John. "Biomimicry: Architecture That Imitates Life." *Harvard Magazine* (2009).

Gómez-Puerto, Gerardo, Enric Munar, and Marcos Nadal. "Preference for curvature: A historical and conceptual framework." *Frontiers in human neuroscience* 9 (2016): 712.

Gutman R (ed) (2009) People and buildings. Transaction, London Hagerhall CM (2000) Clustering predictors of landscape preference in the traditional Swedish cultural landscape: prospect-refuge, mystery, age and management. J Environ Psychol 20(1):83–90

Haigh, Sarah M., Laura Barningham, Monica Berntsen, Louise V. Coutts, Emily ST Hobbs, Jennifer Irabor, Eleanor M. Lever, Peter Tang, and Arnold J. Wilkins. "Discomfort and the cortical haemodynamic response to coloured gratings." *Vision research* 89 (2013): 47-53.

Hibbard, Paul B., and Louise O'Hare. "Uncomfortable images produce non-sparse responses in a model of primary visual cortex." *Royal Society open science* 2, no. 2 (2015): 140535.

Hildebrand, Grant. *The Wright space: pattern and meaning in Frank Lloyd Wright's houses*. Seattle: University of Washington Press, 1991.

Hildebrand, Grant. *Origins of architectural pleasure*. Univ of California Press, 1999.

Jadva, Vasanti, Melissa Hines, and Susan Golombok. "Infants' preferences for toys, colors, and shapes: Sex differences and similarities." *Archives of sexual behavior* 39, no. 6 (2010): 1261-1273.

Juricevic, Igor, Leah Land, Arnold Wilkins, and Michael A. Webster. "Visual discomfort and natural image statistics." *Perception* 39, no. 7 (2010): 884-899.

Le, An TD, Jasmine Payne, Charlotte Clarke, Murphy A. Kelly, Francesca Prudenziati, Elise Armsby, Olivier Penacchio, and Arnold J. Wilkins. "Discomfort from urban scenes: Metabolic consequences." *Landscape and Urban Planning* 160 (2017): 61-68.

Leder, Helmut, Benno Belke, Andries Oeberst, and Dorothee Augustin. "A model of aesthetic appreciation and aesthetic judgments." *British journal of psychology* 95, no. 4 (2004): 489-508.

Leder, Helmut, and Claus-Christian Carbon. "Dimensions in appreciation of car interior design." *Applied Cognitive Psychology* 19, no. 5 (2005): 603-618.

Leder, Helmut, Pablo PL Tinio, and Moshe Bar. "Emotional valence modulates the preference for curved objects." *Perception* 40, no. 6 (2011): 649-655.

Lederman, Roy R., and Ronen Talmon. "Learning the geometry of common latent variables using alternating-diffusion." *Applied and Computational Harmonic Analysis* 44, no. 3 (2018): 509-536.

Lidwell, William, Kritina Holden, and Jill Butler. *Universal principles of design, revised and updated: 125 ways to enhance usability, influence perception, increase appeal, make better design decisions, and teach through design*. Rockport Pub, 2010.

Lippman, Peter C. *Evidence-based design of elementary and secondary schools: A responsive approach to creating learning environments*. John Wiley & Sons, 2010.

LoBue, Vanessa. "Deconstructing the snake: The relative roles of perception, cognition, and emotion on threat detection." *Emotion* 14, no. 4 (2014): 701.

Maass, Anne, Ilaria Merici, Erica Villafranca, Rosaria Furlani, Elena Gaburro, Anna Getrevi, and Margherita Masserini. "Intimidating buildings: can courthouse architecture affect perceived likelihood of conviction?." *Environment and behavior* 32, no. 5 (2000): 674-683.

Mastandrea, Stefano, Gabriella Bartoli, and Giuseppe Carrus. "The automatic aesthetic evaluation of different art and architectural styles." *Psychology of Aesthetics, Creativity, and the Arts* 5, no. 2 (2011): 126.

Mastandrea, Stefano, and Fridanna Maricchiolo. "Implicit and explicit aesthetic evaluation of design objects." *Art & Perception* 2, no. 1-2 (2014): 141-162.

Maydeu-Olivares, Alberto, and Ulf Böckenholt. "Modeling preference data." *The SAGE handbook of quantitative methods in psychology* (2009): 264-282.

McManus, I. Chris, and Wen Wu. "“The square is… bulky, heavy, contented, plain, good-natured, stupid…”: A cross-cultural study of the aesthetics and meanings of rectangles." *Psychology of Aesthetics, Creativity, and the Arts* 7, no. 2 (2013): 130.

Munar, Enric, Gerardo Gómez-Puerto, Josep Call, and Marcos Nadal. "Common visual preference for curved contours in humans and great apes." *PloS one* 10, no. 11 (2015): e0141106.

Okada, Akinori, and Tadashi Imaizumi. "Nonmetric multidimensional scaling of asymmetric proximities." *Behaviormetrika* 14, no. 21 (1987): 81-96.

Palladio, Andrea. 1997. *Andrea Palladio: The Four Books on Architecture. (I Quattro libri dell'architettura.)* Translated and edited by Tavernor, R., Schofield, R., Cambridge: MIT Press (Original work published 1570).

Palumbo, Letizia, and Marco Bertamini. "The curvature effect: A comparison between preference tasks." *Empirical Studies of the Arts* 34, no. 1 (2016): 35-52.

Palumbo, Letizia, Nicole Ruta, and Marco Bertamini. "Comparing angular and curved shapes in terms of implicit associations and approach/avoidance responses." *PloS one* 10, no. 10 (2015): e0140043.

Penacchio, Olivier, and Arnold J. Wilkins. "Visual discomfort and the spatial distribution of Fourier energy." *Vision research* 108 (2015): 1-7.

Penacchio, Olivier, Arnold J. Wilkins, Xavier Otazu, and Julie M. Harris. 2016, August. "Inhibitory function and its contribution to cortical hyperexcitability and visual discomfort as assessed by a computation model of cortical function." In *Perception* 45, pp. 272-272. Olivers Yard, 55 City Road, London EC1Y 1SP, England: Sage Publications LTD.

Penacchio, Olivier, Xavier Otazu, and Laura Dempere-Marco. "A neurodynamical model of brightness induction in v1." *PloS one* 8, no. 5 (2013): e64086.

Piccolo, Domenico. "Observed information matrix for MUB models." *Quaderni di Statistica* 8 (2006): 33-78.

Reber, Rolf, Norbert Schwarz, and Piotr Winkielman. "Processing fluency and aesthetic pleasure: Is beauty in the perceiver's processing experience?." *Personality and social psychology review* 8, no. 4 (2004): 364-382.

Redies, Christoph. "A universal model of esthetic perception based on the sensory coding of natural stimuli." *Spatial vision* 21, no. 1 (2007): 97-117.

Shaftoe, Henry. *Convivial urban spaces: Creating effective public places*. Earthscan, 2012.

Silvia, Paul J., and Christopher M. Barona. "Do people prefer curved objects? Angularity, expertise, and aesthetic preference." *Empirical studies of the arts* 27, no. 1 (2009): 25-42.

Sullivan, Louis H. "The tall office building artistically considered." *Lippincott's Magazine* 57, no. 3 (1896): 406.

Talmon, Ronen, Stéphane Mallat, Hitten Zaveri, and Ronald R. Coifman. "Manifold learning for latent variable inference in dynamical systems." *IEEE Transactions on Signal Processing*63, no. 15 (2015): 3843-3856.

Zhang, Ting, and Hua Dong. 'Human-centred design: an emergent conceptual model', Include2009, Royal College of Art, April 8-10, 2009, London Include2009 proceedings (2009). Retrieved from: http://www.hhc.rca.ac.uk/2084/all/1/proceedings.aspx

Vartanian, Oshin, Gorka Navarrete, Anjan Chatterjee, Lars Brorson Fich, Jose Luis Gonzalez-Mora, Helmut Leder, Cristián Modrono, Marcos Nadal, Nicolai Rostrup, and Martin Skov. "Architectural design and the brain: effects of ceiling height and perceived enclosure on beauty judgments and approach-avoidance decisions." *Journal of environmental psychology* 41 (2015): 10-18.

Vartanian, Oshin, Gorka, Navarrete, Anjan, Chatterjee, Lars Brorson, Fich, Helmut, Leder, Cristián, Modroño, Marcos, Nadal, Nicolai, Rostrup, and Martin, Skov. "Impact of contour on aesthetic judgments and approach-avoidance decisions in architecture." *Proceedings of the National Academy of Sciences* 110, no. Supplement 2 (2013): 10446-10453.

Vitruvius, Marcus Pollio. 1914. Translated by Morris, Hicky Morgan, *Vitruvius: The Ten Books on Architecture.* (*De Architectura*.) Cambridge: Harvard University Press. Retrieved from: http://www.gutenberg.org/files/20239/20239-h/20239-h.htm (Original work published 15 B.C.).

Lloyd Wright, F. "The living city." *New York: Horizon* (1958).

Zajonc, Robert B. "Attitudinal effects of mere exposure." *Journal of personality and social psychology* 9, no. 2p2 (1968): 1.

Zhaoping, Li, and Peter Dayan. "Pre-attentive visual selection." *Neural Networks* 19, no. 9 (2006): 1437-1439.

	First	Second	Third	Fourth
A	15	5	3	1
B	5	13	6	0
C	1	0	2	21
D	3	6	13	2

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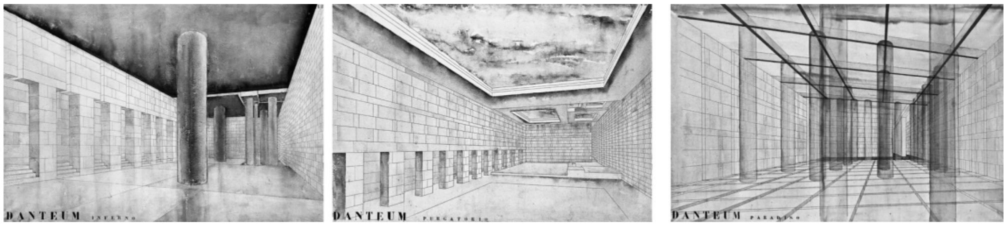

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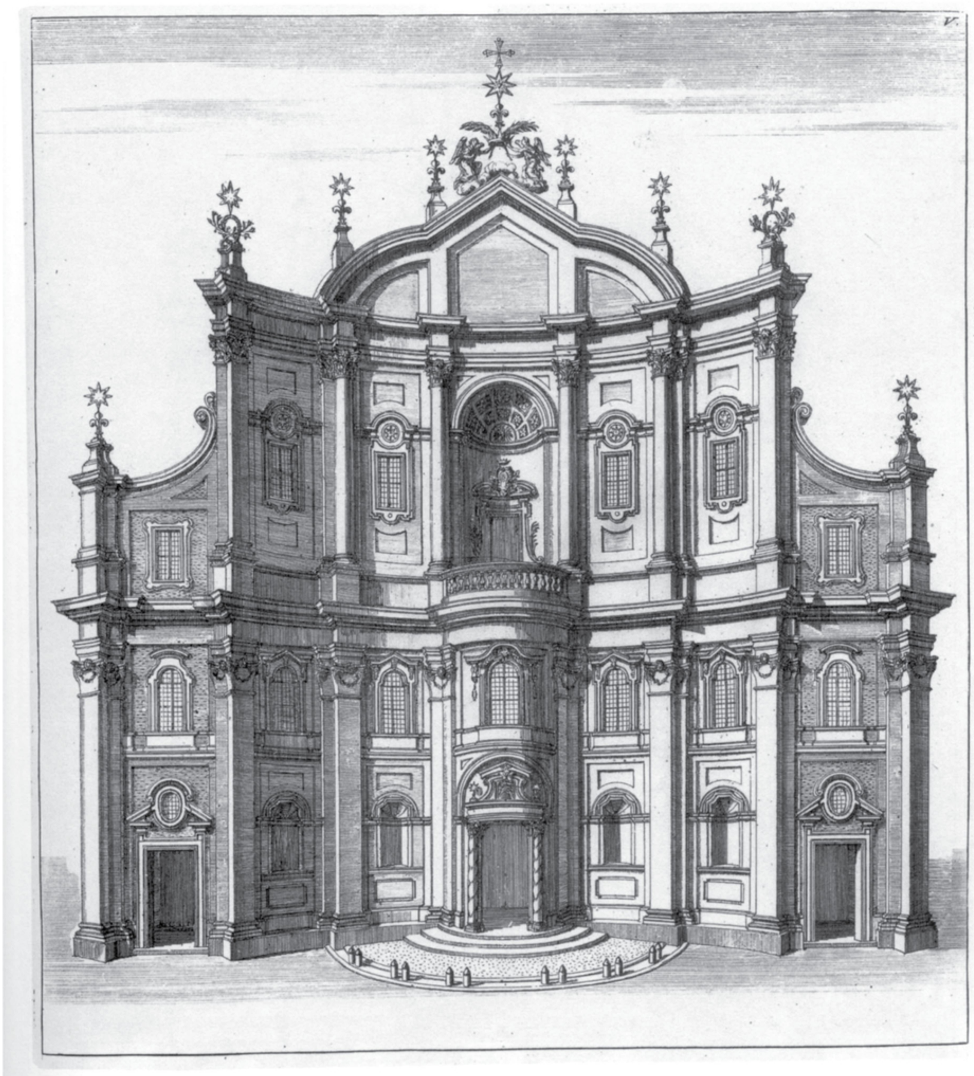

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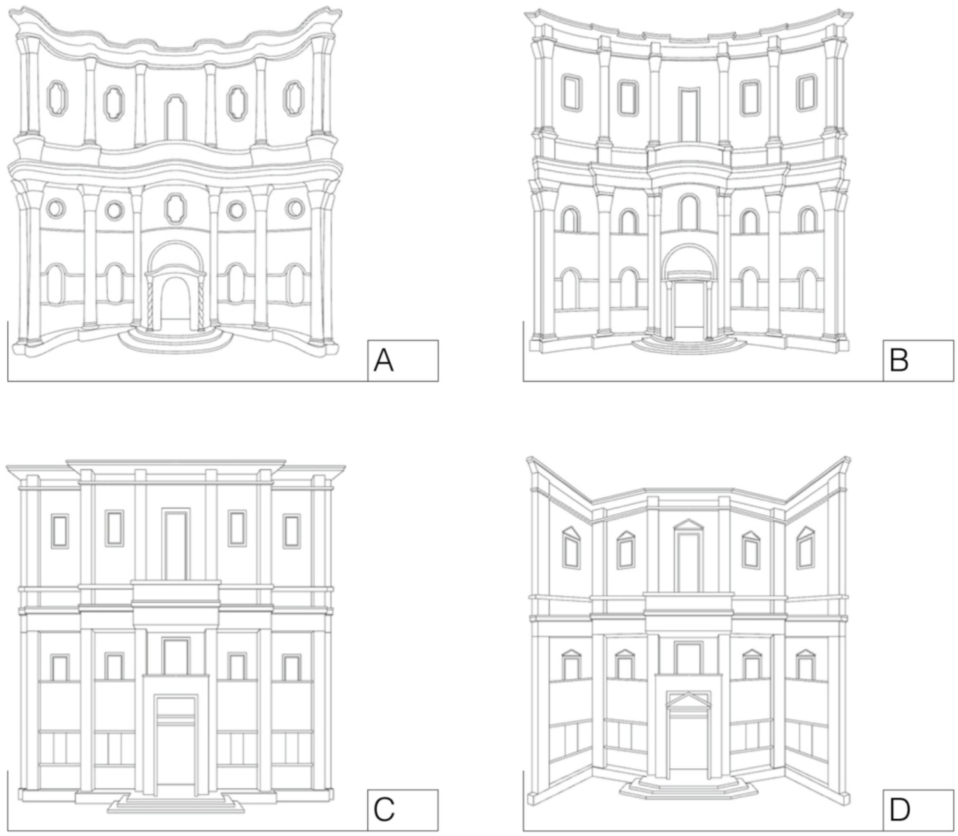

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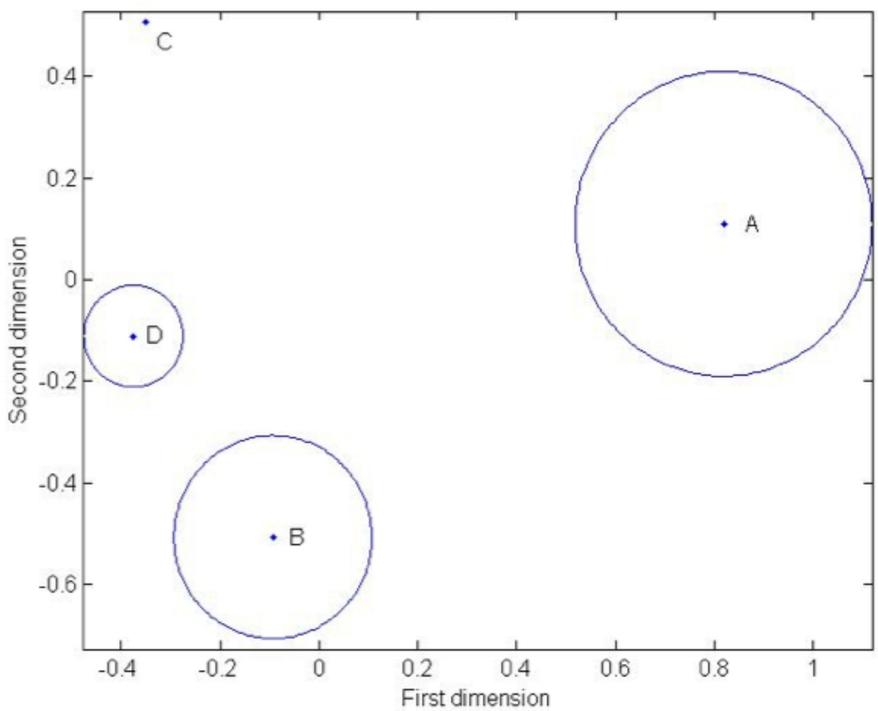

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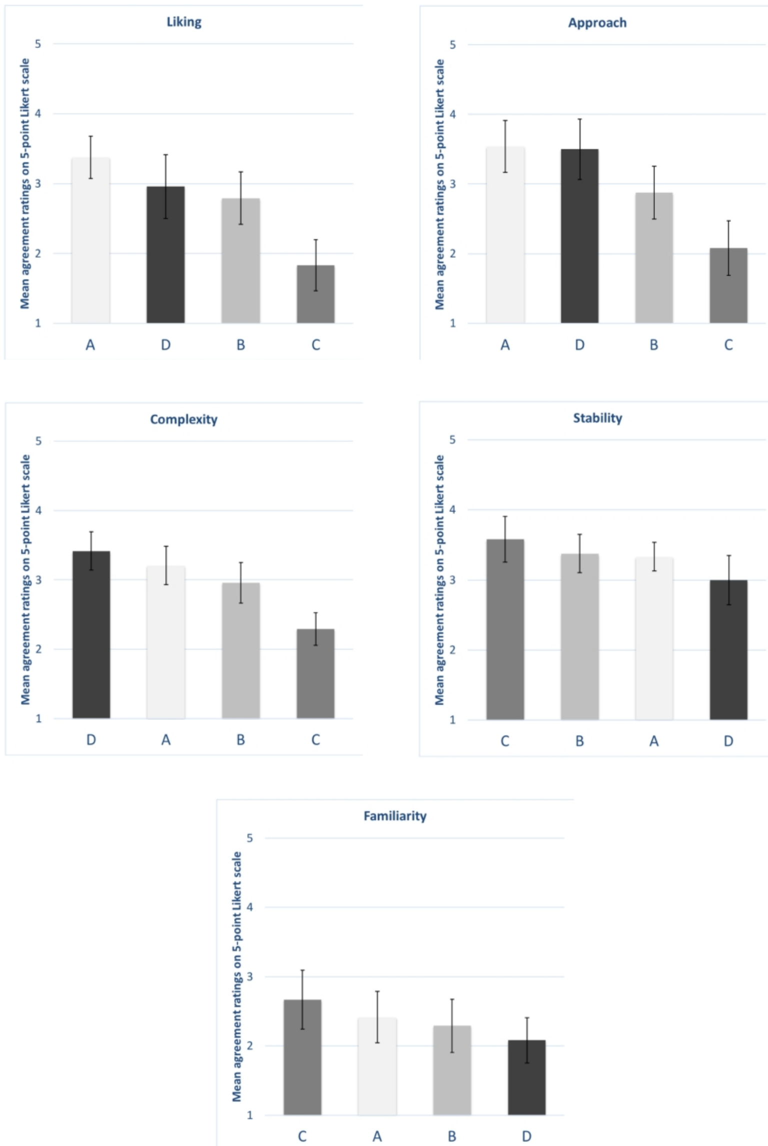

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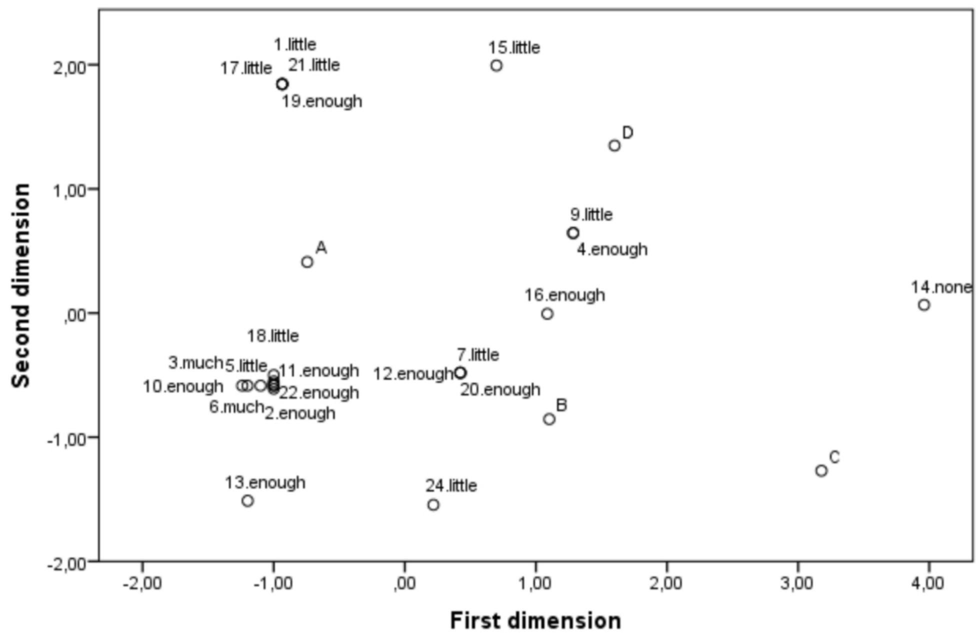

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